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Matthew R. Gilpin, David B. Scharfe, and Anthony P. Pancotti

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AFRL/RZSA
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

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14. ABSTRACT

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Molten Boron Phase-Change Thermal Energy Storage to Augment Solar Thermal Propulsion Systems

Matthew R. Gilpin[1]
University of Southern California, Los Angeles, CA, 90089

David B. Scharfe[2]
ERC, Inc., Edwards AFB, CA 93524

Marcus P. Young[3]
Air Force Research Laboratory, Edwards AFB, CA, 93524

and

Anthony P. Pancotti[4]
MSNW LLC, Redmond, WA, 98052

Solar thermal propulsion offers a unique combination of high thrust and high specific impulse levels that can provide competitive advantages relative to traditional satellite propulsion systems. In order to enhance the functionality of this technology, thermal storage combined with a means of thermal-to-electric conversion is suggested, with the idea of providing a dual-mode power and propulsion system based on thermal energy. A system including boron phase change material for storing energy, an insulating containment system consisting of boron nitride, carbon bonded carbon fiber, and vacuum gap insulation is proposed, with thermophotovoltaics used for electrical conversion. A laboratory solar concentration system has been constructed and experiments to directly heat small quantities of boron have begun, so that the nature and challenges of this system can be evaluated.

Nomenclature

ΔV	=	Velocity increment
γ	=	Ratio of specific heats
g	=	Earth's gravitational constant
I_{sp}	=	Specific impulse
k_B	=	Boltzmann's Constant
m	=	Particle mass
P	=	Pressure
P_e	=	Exit pressure
T	=	Temperature
T_h	=	Hot-side temperature
V_e	=	Exit velocity

I. Introduction

SOLAR Thermal Propulsion (STP) systems, with a unique balance between propulsive efficiency and available thrust, are known to offer significant advantages over chemical and electric propulsion for some mission

[1] Graduate Student, AME Department, 854 W. 36th Pl., RRB 101, AIAA Member.
[2] Research Scientist, Advanced Propulsion Concepts Group, 10 E. Saturn Blvd., AIAA Member.
[3] Program Manager, Advanced Propulsion Concepts Group, 10 E. Saturn Blvd., AIAA Member.
[4] Propulsion Research Scientist, MSNW LLC, 8551 154th Ave., AIAA Member.

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scenarios. A recent review of propulsion technologies[1] has indicated the particularly strong potential performance offered by Solar Thermal Propulsion in microsatellite systems. Analysis shows that STP systems currently in development, with specific impulse (I_{sp}) values of 400-1000 seconds, can provide a propulsion system mass fraction (including propellant) of less than 50%, with a 1.5 km/s velocity increment (ΔV) capability. With microsatellite STP thrust levels of 1 Newton, the entire velocity increment could plausibly be delivered in less than one day, providing the potential for a highly capable, light-weight spacecraft.[1]

Traditionally, however, STP has been viewed as somewhat limited due to the requirement for solar illumination of the collector during times when propulsion is needed. Proposed fiber optic collection of concentrated sunlight can yield some extra flexibility in terms of spacecraft attitude and positioning by decoupling precisely-aimed collectors from the thruster and other physical components.[2-6] Combining STP with a means of thermal storage, however, would allow for augmented thrust even during times of spacecraft eclipse, and could vastly increase the utility of the propulsion system for a variety of missions; adequate thermal storage could potentially yield a high-efficiency, high-thrust spacecraft that can produce thrust on-demand even when in eclipse, offering the flexibility of a conventional chemical or electric system with the superior performance and robustness of an STP system. Further, a thermal storage system could yield benefits in terms of augmented thrust relative to a similarly sized non-storage STP system if both direct-gain solar illumination and stored thermal energy can be used simultaneously; this sort of design could likewise be used to decrease the size of the overall solar concentration system for a spacecraft with only intermittent propulsion requirements.[2]

An additional perceived disadvantage of an STP system is the need for additional large solar concentrators. While the electrical power requirements for chemical and electrical rockets can generally be met via the power subsystem (i.e.: photovoltaic cells and batteries) on board the spacecraft, the solar thermal propulsion system would require its own, additional, dedicated solar collection and concentration system. This thermal collection system requires an additional budget for space and mass onboard the satellite and launch vehicle, appearing as a significant disadvantage for the propulsion technology. It is suggested here, however, that the use of an effective thermal storage system, combined with a means to convert thermal energy to on-demand electrical power, could eliminate the need for photovoltaic systems and accompanying batteries. Powering the entire spacecraft, including both electrical and propulsive needs, via a thermal collection, concentration, storage, and conversion system, could yield a highly efficient and high performance satellite system.

This paper will analyze the prospect of utilizing a solar thermal system with thermal storage as the primary energy source and propulsive device on board a microsatellite. This study will not offer a complete design of any particular subsystem, but will seek to survey each area of technological interest for such a thermal power and propulsion system. The details of an ongoing experimental effort to characterize the nature of concentrated solar power systems and thermal storage materials will also be discussed.

II. Propulsion and ΔV for Microsatellites

A large variety of solar thermal propulsion systems for microsatellites have been proposed and studied in ground tests and simulations.[4-10] However, no solar thermal rockets, much less those intended for microsatellites, have ever been flown[10]. The literature does note that a well-implemented STP system on board a microsatellite would be a significantly enabling technology due, in part, to the fact that microsatellites are often launched as secondary payloads accompanying higher budget missions, and are therefore typically placed in sub-optimal orbits for their own mission goals. In many cases, the required ΔV to reposition the microsatellite into the desired orbit is several hundred meters per second, with the more extreme cases requiring up to 2 km/s. Present propulsion technologies utilized on microsatellites are inadequate for this purpose.[1]

It has been noted that providing a microsatellite with an STP system could allow up to a 1.5-2 km/s ΔV maneuver, opening up a wide range of mission scenarios. By providing a ΔV of several hundred meters per second or larger, the microsatellite operating regime (assuming various starting orbits as a secondary payload) could be widened to include maneuvers from Geosynchronous Transfer Orbit (GTO) to Geosynchronous Earth Orbit (GEO), insertion into lunar orbit, highly eccentric orbits for observation and analysis, LaGrange point and Earth-trailing orbits, and even Earth escape.[7] Even end-of-life deorbiting of microsatellites would be economical with an STP system.[9] Table 1 lists some mission scenarios and the required ΔV values that have been studied. Note that while these missions may also be possible with electric propulsion systems, the time to complete the maneuver via STP would be significantly reduced, perhaps by a factor of three or greater depending on the burn strategy selected (e.g.: continuous firing of thrusters vs. firing only at apogee and/or perigee).

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Table 1. Example Missions for Microsatellite STP System Studies.[7]

Mission Description	Required range of ΔV [m/s]
Near Escape: *Assumes starting from GTO, and maneuvering for flybys of near-Earth objects, magnetospheric characterization in highly eccentric Earth orbits, positioning at LaGrange points, or Earth-trailing orbits.*	*770-1,770*
GEO Insertion: *Assumes starting from GTO and transferring to geosynchronous Earth orbit*	~1,760
Other Body Capture: *Assumes starting from a fly-by orbit and subsequent capture into lunar or planetary orbit.*	1,100-4,000
- Lunar Orbit Insertion:	2,103

In addition to these somewhat exotic mission scenarios, an STP system could be utilized to provide a highly dynamic and responsive microsatellite, or to simply reposition a non-optimally placed satellite to a new inclination, orbit altitude, or orbit phase. A calculation of the combinations of inclination change and altitude change from a circular 200 km orbit that becomes possible with large ΔV values is provided in Figure 1. In producing this plot, it was assumed that altitude change maneuvers utilized a Hohmann transfer (or series of Hohmann-type burns at perigee and apogee), and that any inclination change was completed at high altitude. Attitude control, precise approach to another orbiting body, and minor orbit rephasing are likely to consume significantly less ΔV than major changes to the altitude or inclination of the orbit.

III. Solar Thermal Power and Propulsion System

Previous studies have examined the prospect of STP with thermal storage;[2,3] major developmental projects, including the Solar Orbit Transfer Vehicle (SOTV)[11-14] and the Integrated Solar Upper Stage (ISUS),[15,16] included both thermal storage and a means of thermal electric generation. Typically, however, thermal storage systems proposed for STP satellites are based on the sensible heat in a solid material such as graphite. The key difference to

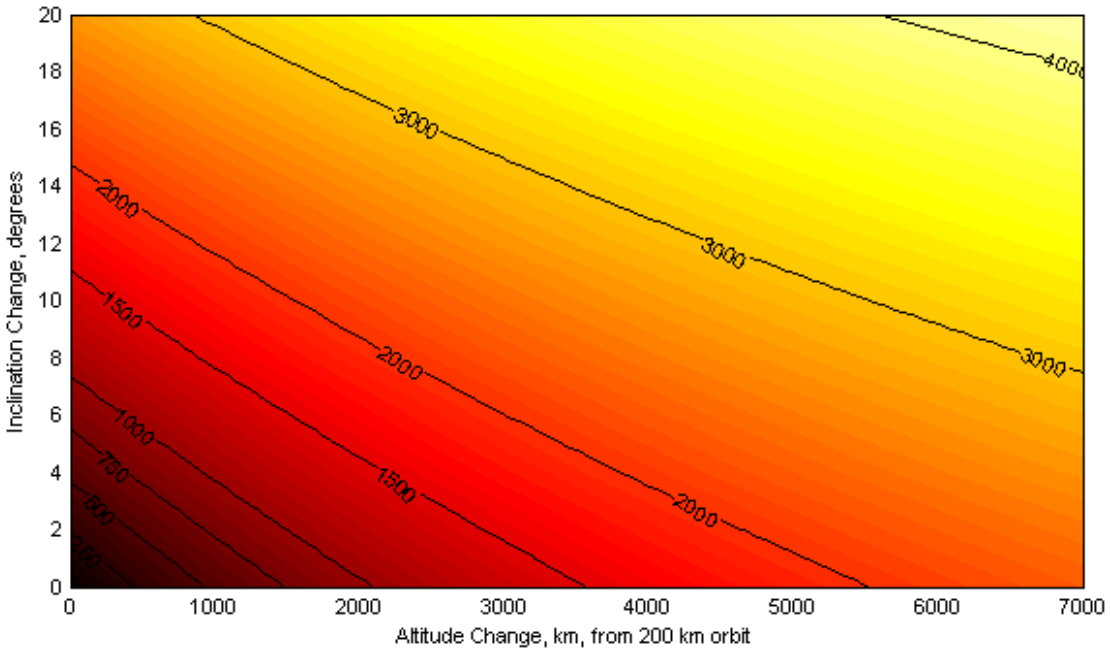

Figure 1: Color map and contours indicating the required ΔV values to achieve a given combination of altitude increase and inclination change. Units of ΔV, indicated on the contours, are given in m/s.

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be explored here is the optimization of thermal storage using a phase change material (PCM), which should allow for a greater energy density of the storage system, combined with relatively constant-temperature operation. Additionally, while high-performance full-sized satellites are currently available, practical designs and propulsion systems for microsatellites with large ΔV capabilities and high thrust levels (i.e.: rapid response time) are not. With this in mind, the target will be to devise a system that competes favorably against traditional chemical and electric rockets coupled to battery-based electrical systems. The goal of this work is to edge closer to a full bimodal thermal power and propulsion system design through determination of current materials capabilities and analysis of technological developments (in terms of material properties and system designs) required to make such a system feasible and competitive. The basic targets for the final system require providing capabilities for a 100 kg microsatellite in Low Earth Orbit (LEO) including continuously available electrical power rated at 100 Watts, continuously available propulsion with performance on the order of 1 Newton of thrust and a 300-400 second I_{sp}, an energy collection system capable of drawing in several hundred Watts per kg, and an energy storage density of at least 750 kJ/kg.[17] If these goals can be met via the proposed bimodal system, then significant improvement relative to conventional chemical or electrical rockets, along with conventional photovoltaic and battery power systems, will be shown, and a significant advancement in the utility of microsatellites will be plausible.

A. Propulsion Requirements

The most critical requirement for the proposed bimodal thermal system will be to ensure optimal operation of the propulsion mechanism. In order to provide a propulsion system that not only competes with existing flight-ready technologies, but also demonstrates enough significant advantages that a full redesign of the satellite power system is justified, we must demand high performance of an STP system. The primary competitors for the high-thrust, mid-I_{sp} capabilities of an STP system are in-space chemical and electric rockets. In order to compete with these systems, an STP system must provide similar or greater thrust relative to a chemical rocket, with a notable increase in I_{sp}. It has been shown in the literature that an STP system sized for a microsatellite is capable of producing a relatively high thrust level of 1 Newton.[1,5] In order to surpass the best chemical systems available for microsatellites, a target I_{sp} in the range of 300-400 s is the goal, and is certainly achievable.[1,3,5]

The primary propellant options discussed in the literature for STP systems are hydrogen and ammonia. Hydrogen can offer I_{sp} values on the order of 1000 s, but is not space-storable.[2] Ammonia, on the other hand, is readily storable in space, and several studies show that with a pre-nozzle temperature above 2500 K, I_{sp} values of 407 s can be achieved.[2,5] Ammonia propellant also offers additional advantages in terms of system simplicity: the vapor pressure of the ammonia propellant can be used to pressurize the propellant and move it from the storage tank to the thruster,[2] so an active feed system is not required. Ammonia thermally dissociates into hydrogen and nitrogen at high temperatures; this provides lighter exhaust species that can be ejected at higher velocity. However, this comes with the simultaneous disadvantage of the absorption of significant heat when bonds are broken.[4]

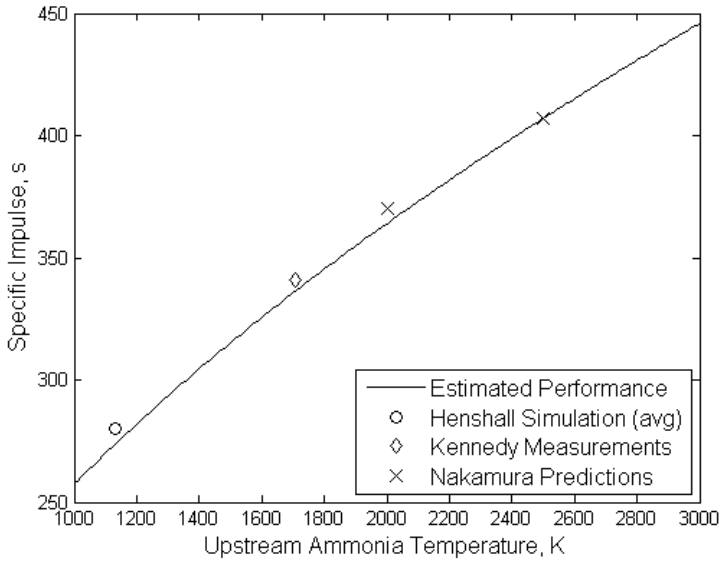

Figure 2: I_{sp} vs. upstream temperature for an ammonia-fueled solar thermal rocket. Note the strong agreement between the assumed model and data from the literature.[3-5]

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Theoretically, the exhaust velocity and the I_{sp} of a rocket can be calculated as:

$$V_e = I_{sp} g = \sqrt{\frac{Tk_B}{m}\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{P_e}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]}, \quad (1)$$

where V_e is the exhaust velocity, T and P are the upstream propellant temperature and pressure, respectively, P_e is the exit pressure from the nozzle, m is the average propellant particle mass, γ is the ratio of specific heats for the propellant, g is Earth's gravitational constant, and k_B is Boltzmann's constant.

Direct calculation of the exhaust velocity from temperature alone requires assumptions of the upstream pressure, the degree of disassociation of ammonia (a function of temperature and time[18]), and calculations based on the nozzle area ratio to determine the exit pressure. Additionally, even with the assumption that ammonia does not disassociate, the ratio of specific heats, γ, will vary with temperature. At low temperatures, in which only the translational and rotational modes of molecular motion are activated, γ for pure ammonia is given as 1.31. As temperature increases and the 6 vibrational modes are activated, the ratio of specific heats will decrease, ultimately yielding a γ value closer to 1.1. A combination of varying energy states and ammonia molecules that can disassociate into nitrogen and hydrogen[18] represents a significantly complex problem.

Therefore, for this analysis, we will choose a basis value that has been noted in the literature: a temperature of 2500 K for ammonia should yield an I_{sp} of 407 s in a typical solar thermal rocket.[2,5] For estimating performance with varying temperature, a rough scaling with the square root of T is utilized; the result is displayed in Figure 2. Note that the estimated performance curve closely approximates predicted and measured performance of solar thermal rockets under development.

Throughout the rest of this paper, the analysis will focus on the requirements associated with concentrating solar flux onto a thermal storage medium in order to achieve something near the 2500 K target temperature. This requires a solar concentration ratio of 10,000:1,[2,14] which has been demonstrated experimentally.[4] The thermal storage medium must be able to adequately store energy in this temperature regime, and insulators need be able to maintain that temperature for a significant amount of time during eclipse. Further, a heat exchanger for transferring energy from the thermal storage medium to the propellant must be developed, and a means of thermal-electric conversion will need to be devised. All materials in contact with the thermal storage medium must, of course, tolerate the highest system temperatures without undergoing significant chemical or physical changes.

B. Thermal Collection

The collection of thermal energy from the sun appears to be a solved problem, with collectors appropriately designed for in-space use that achieve concentration ratios over 10,000:1 in ground-based experiments.[4] There is significant confidence that an adequate solar concentration and collection system can be designed to produce temperatures over 3000 K, and that the target temperature of 2500 K[18] can certainly be achieved.[5]

Variations of solar concentration and collection exist in currently developed STP designs, in ground-based solar thermal power generation, and even in concentrated photovoltaic systems with both terrestrial and space-based applications. Proposed designs for propulsion systems include parabolic, spherical, and Fresnel concentrators used to focus sunlight by orders of magnitude onto a small surface.[2,4] For light-weight, imperfect primary concentrators, small secondary concentrators (with high temperature handling capabilities) can be added to more precisely focus the collected light.[2] Concentrator designs include inflatable and deployable systems as well as light-weight rigid mirrors;[2,4,5,11-14] concentrator masses below 1 kg per square meter are common,[2] and concentrators weighing under 200 g/m^2 while providing a concentration ratio near 10,000:1 have been shown.[4,9,19] Concentrator mass will certainly compete well with that of a photovoltaic (PV) system. Further, due to the higher efficiency of solar reflection compared to photoelectric conversion, the size of a concentrating system can be notably smaller while providing the same power output. The use of fiber optic lines to couple together the collected light from multiple small concentrators could also result in a decrease in the mass of an STP system since smaller concentrators may have a much lighter mass for a given surface area.[2-4]

It is expected than an efficiency of greater than 70% for the entire solar collection system can be achieved; this includes inefficiencies associated with collecting (reflecting) and concentrating the incident light, collecting and transmitting the concentrated light along a fiber optic cable, and delivering it to the thermal storage medium.[5] Designed concentrators can achieve 3300 K or higher as shown by Nakamura, et al.[5] It should be noted, however, that current engineering systems in the lab are only 35% efficient. Even at this lab prototype level, the efficiency is close to that of high-end triple-junction PV panels for use in space, although the "downstream" efficiencies of a solar

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thermal system will likely be considerably less than that of the simple batteries and power supplies that might be used to handle PV-generated energy. However, Nakamura[5] indicates that there are a few simple upgrades to his basic engineering systems that would more than double the overall efficiency. For example, a relative efficiency increase of 9% will be achieved by simply operating the solar concentrators in space where conditions of the air will not affect the path of light.[5] Additionally, Nakamura, et al., state that in laboratory models, a concentrator with a reflectivity of 80% was used; reflectivity above 90% requires only careful engineering.[5] Targeting these and a few other minor design improvements, researchers expect overall efficiencies over 70% for a fully space-qualified collection system. There is, however, some disagreement as to the absolute maximum that can be achieved: Henshall, et al., for example, place the fiber optic transmission efficiency at a maximum of 80%,[2,3] while Nakamura suggests that 90% is readily achievable.[5] Significant improvement over the 35% starting point, however, is certainly likely as a system is developed and optimized for use in space.[5] With the expected improvements in optical system efficiency achieved, well-designed storage, heat transfer, and electrical conversion subsystems should be able to achieve a marked step forward relative to traditional PV-battery systems.

C. Thermal Storage Materials

Materials typically used for terrestrial thermal storage systems are not applicable to microsatellite power systems like that proposed here: the range of operating temperatures and the energy storage density are both too low.[17] However, the basic concepts of terrestrial thermal storage systems can provide the direction of investigation for in-space systems. In this regard, it can be learned that storing thermal energy can generally be accomplished by either a sensible heat system, which operates on the principle of raising the temperature of a material with a high specific heat, or by a latent heat system, which operates on the principle of energy storage due to the change of state or phase (typically the solid-liquid transition) of a material.

In evaluating the potential of a microsatellite system with sensible heat storage, materials with melting points significantly above the planned operation temperature were reviewed. Table 2 summarizes the relevant properties for candidate high temperature sensible heat energy storage materials. The materials below the dashed line are applicable for phase change applications and other support roles, and are included for completeness.

Previous work on sensible heat thermal energy storage for spacecraft applications has determined that boron carbide and carbon were optimum materials for the applications studied.[7] The performance of these materials is ultimately limited by the allowable temperature change defined by mission requirements. Larger temperature changes will reduce the power conversion efficiency, cause variations in thruster performance, and place additional stress on materials due to temperature cycling. For this reason, even these high-performance materials are unlikely to compete with a latent heat energy storage system that can achieve a similar or greater energy storage density for spacecraft applications, while maintaining a relatively constant temperature.

When considering a latent heat energy storage system, in which the energy storage comes primarily by way of a material that changes phase, additional difficulties must be addressed and additional structural concerns must be considered (i.e.: containing a liquid at high temperature). Further, there are numerous considerations when choosing a high-temperature phase change material for the solar thermal power and propulsion system proposed here. Table 3

Table 2. Relevant Properties for Candidate High Temperature Sensible Heat Storage Materials.[7]

Material	T_{melt} [K]	$c_{p,s}$ [kJ/kgK]	$\Delta E/m_{2000\text{-}2600K}$ [MJ/kg]	ΔH_{fus} [kJ/kg]
Carbon	*3923*	*2.09*	*1.25*	---
Tungsten	3643	0.134	0.0804	284
Rhenium	3453	0.15	0.09	325
Boron Nitride	3273	1.99	1.194	---
BeO	3010	2.43	1.458	3,410
Molybdenum	2890	0.255	0.153	391
Silicon Carbide	2818	1.47	0.882	---
B_4C	*2673*	*2.51*	*1.506*	*1,900*
Boron	2570	2.93		4,650
Al_2O_3	2322	1.36		4,580
Silicon Nitride	2173	1.13		---
Silicon	1685	0.963		1,800

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Table 3. High Temperature Phase Change Material Considerations.

PCM Consideration
- Properly Matched Melting Temperature.
- High Energy Density.
- Good Material Stability.
- Good Material Compatibility.
- High Thermal Conductivity.
- Low Vapor Pressure at Melting Temperature.
- Small Volume Change During Transition.
- High Emissivity.

Table 4. Potential High-Temperature Phase Change Materials.

Material	Melting Temp. [K]	Heat of Fusion [kJ/kg]	Thermal Conductivity [W/mK]
Manganese	1519	235	7.8
Magnesium Fluoride	1536	940	
Beryllium	1560	1312	200
Silicon	***1687***	***1785***	***149***
Nickel	1728	298	90.9
Cobalt	1768	272	100
Yttrium	1799	128	17.2
Iron	1811	247	80.4
Scandium	1814	313	15.8
Palladium	1828	157	71.8
SiO_2	1923	188	~1
Lutetium	1925	126	16.4
Titanium	1941	295	21.9
Zirconium	2128	153	22.7
Chromium	2180	403	93.9
Vanadium	2183	422	30.7
Rhodium	2237	258	150
Boron	***2570***	***4600***	***27.4***
Hafnium	2506	152	23.2
Ruthenium	2607	381	117
Iridium	2739	213	147
Niobium	2750	323	53.7
Molybdenum	2896	390	138

lists the most important considerations that were assembled from previous material reviews and from the early analysis in the present work. The first two properties, melting temperature and energy density, are critical enabling considerations, while the others also play a strong role.

A thorough search was conducted for phase change materials that met the melting temperature and energy density requirements. Table 4 shows the most promising materials identified during the investigation. For the high-performance microsatellite system described here, boron has been selected as the thermal storage medium. Boron has the highest energy density (4.6MJ/kg) and a melting temperature that coincides well with the optimal operating temperature of an ammonia-fueled STP rocket. However, limited research has gone into using the material at high temperatures. Therefore, one of the key goals of this research project is to evaluate the use of boron in terms of its energy storage capacity, reusability over repeated cycling, and interaction with other materials in the system.

D. Phase Change Material Containment and Insulation

The primary added complication for latent heat energy storage, versus sensible heat energy storage, is that the latent heat system will require a storage container made from a material that is chemically compatible with the PCM and structurally sound at high temperatures. The material must maintain these properties during high temperature operation for long periods of time, perhaps 10 years or more. The case material adds to the mass of the system and reduces the effective energy storage density. The container material selection is made primarily through

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Table 5. Properties of High-Temperature Insulation Materials.

Material	Density [kg/m^3]	T_{melt} [K]	$k_{th,500K}$ [W/mK]	$k_{th,1000K}$ [W/mK]	$k_{th,1500K}$ [W/mK]	$k_{th,2000K}$ [W/mK]	$k_{th,2500K}$ [W/mK]
Aerogel[20]	80	600	0.01				
Fused Silica[21]	2200	1985	1.5	2.1	2.1		
Saphire[22]	4000	2313	20	8	---	---	
Alumina[22]	4000	2345	21	5	5	8	
Boron Carbide[23]	2520	2673	12.5	9	6.5	---	---
Silicon Carbide[24]	3210	3003	120	60	38	28	---
Boron Nitride[21]	3487	3246	37	22	21	19	---
Carbon Bonded Carbon Fiber[25]	180	3273	---	0.4	---	0.9	---
Vacuum [Δx=1cm]	---	---	0.15	0.80	2.39	5.33	10.1

compatibility considerations and is therefore completely coupled to the chosen phase change material. Molten boron is highly reactive with a variety of elements, and while the literature concerning molten boron compatibility is limited, materials exist that appear capable of resisting boron attack, as will be discussed in the experimental section of this paper.

Another critical technology required for containing the molten boron phase change material will be preventing the escape of stored energy. Very high temperature thermal insulation materials must meet a long list of exacting requirements, including the ability to withstand the storage temperatures, potentially operate through a number of thermal cycles, be compatible with the other materials involved, and maintain certain structural properties. The present work is focused on systems operating in the temperature range near 2500K. Table 5 lists a select group of common high temperature thermal insulation materials along with a select group of other materials that represent high-performance for other select required properties. Aerogel is listed to illustrate the relevant properties for a material that is fully optimized for minimum thermal conductivity. However, it clearly cannot meet the high temperature stability requirement for the applications discussed here. Carbon bonded carbon fiber (CBCF) appears to be an excellent insulator at the high temperatures required for the proposed system. The effective thermal conductivity for blackbody radiation transport across a 1 cm vacuum gap from a surface at the specified temperature to a surface at 300 K is also given for reference. It is common for solar thermophotovoltaic (TPV) systems to use a vacuum gap with low emissivity surfaces on either side as the first insulating layer.[26]

E. Electric Energy Conversion

There are a wide variety of options for thermal-to-electric systems that operate at a hot-side temperature (T_h) below 1300K and are not mass constrained including thermoelectrics, alkali metal thermoelectric converters (AMTEC), and free piston Stirling engines. These methods, however, would require significant development efforts to operate at the required T_h for high-temperature thermal-to-electric conversion on spacecraft. Closed Brayton cycle systems that can operate at the required high temperatures are not currently available, but it is likely that with further development the technology may be advanced significantly with carbon-carbon systems; Brayton systems are typically the most advantageous for large power levels. Thermionic power conversion systems are also typically more advantageous at higher power levels. Nantenna based conversion systems have significant theoretical potential, but have yet to achieve any significant fraction of this. This leaves thermophotovoltaic systems as the most promising candidate for the near term. TPV systems will be chosen as the representative solution for the discussion to follow. Table 6 provides a summary of the comparison of the states-of-the-art for different energy conversion technologies and comments about the future potential of each technology.

Note that while thermophotovoltaic systems are much heavier than PV at 15 W/kg, TPV will likely benefit from the same type of development that has advanced standard PV over the past decade. In 2001, Kessler noted that state of the art 3-junction photovoltaic arrays developed for space weighed in at 15 W/kg.[28] Surprisingly, this is the same value at which TPV systems sit today. Yet, in just over a decade, NASA is targeting nearly 10 times lighter systems (140 W/kg by 2012).[29] It is reasonable to assume, then, that advanced materials and other developments should push TPV systems down to similar power-per-mass levels in a similar time span.

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Table 6. Electrical Energy Conversion Options.[27]

Technology	Specific Power [W/kg]	Efficiency	Maximum Temperature [K]	Comments
Thermoelectric	9.4	6.3%	1273	• Limited temperature operation. • Incremental development OK for specific power & efficiency.
Thermophotovoltaic	15	19%	None	• Long lifetime demonstration required. • Operation in space environment required.
Thermionic	100@1kWe	> 10%	2200	• Baselined for another application at higher power levels.
AMTEC	14	16%	1300	• Unlikely to achieve required temperatures.
Nantenna	Unknown	<1%	None	• Significant uncertainties in all aspects. • Current concern: efficient rectifying diode.
Closed Brayton	Varies with power	29%	1700	• Possible to achieve required temperatures. • Mass may be high for low power levels.
Free Piston Stirling	100	35%	1050	• Unlikely to achieve required temperatures. • High performance & long lifetime demonstrated.

F. Thermal Conversion for Propulsion

While the majority of the designs for solar thermal propulsion systems do not include a significant means of thermal storage, they can still provide a starting point for the design of the means of heat transfer to the propellant. In typical solar thermal designs, there are two primary means of heating the propellant: either the propellant is heated directly by the concentrated sun light, or the concentrated flux is used to heat an amount of solid material, which then transfers heat to the propellant through convective transfer.[6] Typically, the convective heat transfer method can allow a higher flux of higher temperature propellant, resulting in a more efficient and higher performing vehicle. In the proposed research in which significant thermal energy is stored on-board, this effect would be even more dramatic as the radiation emitted from the phase change material would be even less concentrated than the focused solar flux. Therefore, a convective heat transfer method has been selected for the system proposed here.

In systems designed with sensible heat thermal storage, the convective heat transfer is generally accomplished by flowing the propellant either through a tortuous foam of heated particles or through narrow channels within the storage material.[30,31] While these systems rely on the sensible heat capacity of the material as its temperature increases, they can be used as the basis for designing a system with the high heat capacity and isothermal operation of phase-changing boron. As a first step, for example, the boron nitride-coated boron carbide foam discussed by Kennedy and Palmer[7] could be modified into phase-changing boron particles contained and protected by boron nitride. Likewise, the graphite heat storage and exchange system designed for the ISUS RAC[30,31] could also be modified to contain boron-based storage. It is noted that conduction within a foam of spherical particles to ensure even temperature distribution would present a significant challenge. Additionally, boron is known to react with carbon at high temperatures, so directly incorporating boron into the ISUS RAC system would require layering additional materials for compatibility. As a first design, therefore, it is proposed that the graphite thermal storage block designed for ISUS, with included channels for heating the flowing propellant, be replaced with boron nitride for chemical compatibility with the propellant[7] and the boron phase change material. This boron nitride structure could be further hollowed and filled with boron to allow for phase change thermal storage; the boron nitride structure and channels would serve to contain the boron, to allow additional thermal conduction throughout the thermal storage medium, and to maintain a barrier between the molten boron and the flowing propellant.

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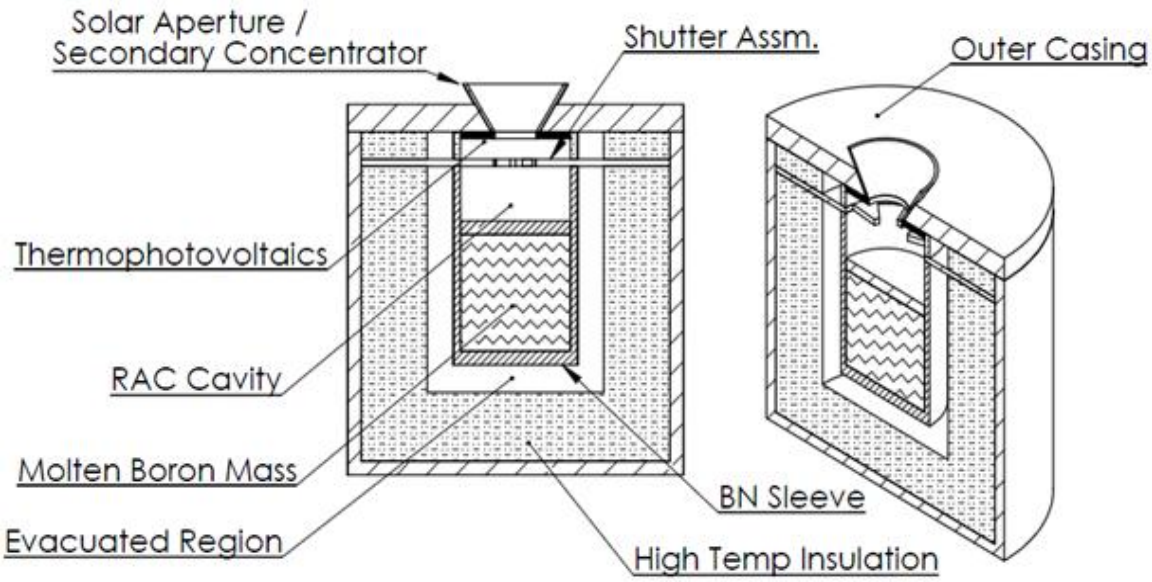

Figure 3. Nominal design for Receiver/Absorber/Converter (RAC) analysis.

G. Preliminary Receiver/Absorber/Converter Design

Combining all of the above components, a baseline system can be imagined. As a first step, the RAC system pictured in Figure 3 is proposed for further analysis and modeling. Note that the system includes a central core of boron phase change material surrounded by boron nitride and that the crucible is insulated with layers of conventional and vacuum insulation. Incoming pre-concentrated solar light enters through the top of the system, as pictured, where a secondary concentrator further focuses the light. Thermophotovoltaics positioned above what is likely to be the hottest surface will convert radiated power to electricity, and a shutter assembly can be used to throttle the system. At this early stage, the means of heat transfer to the propellant has been left out of the design, but can be added in later, either starting from a modification to previous designs (as discussed above) or taking a simulation-suggested design as the heat transfer analysis of the system progresses.

For a high performance microsatellite system in a 100 minute low Earth orbit with 40 minutes in eclipse, a constant electrical draw of 100 Watts combined with a thermal draw of 100 Watts for propulsion is assumed. Allowing for a per-cycle storage efficiency of 75%, and an easily-achieved electrical conversion efficiency of 20%, less than 0.5 kg of boron would be required for energy storage. With a basic insulation design, just over 1 kg of CBCF insulating material would be required; it is assumed that notably less mass would be required with a well designed system combining vacuum insulation and CBCF layers. In this way, an energy density for the storage system of 2-4 times that achievable with conventional lithium ion batteries is likely. Further, assuming a 1360 W/m2 solar constant, and a 50% efficient solar concentration and collection system (an efficiency likely to be exceeded), just over 2 square meters of solar concentrator would be required, weighing well under 0.5 kg.[9] Assuming a reasonable mass level can be achieved with fiber optics used to guide the concentrated solar light, the secondary concentrator, the shutters, and the TPV energy converter, it is likely that the hybrid propulsion and energy storage system for a high performance microsatellite could have a mass of well under 15 kg, leaving a significant mass budget on board a 100 kg microsatellite for propellant and payload.[1]

IV. Experimental Test Facility

In order to develop a practical understanding of the ideas described above, an experimental effort is underway at the University of Southern California to physically investigate phase change thermal energy storage. The near term goal of the system is to generate and maintain a molten boron sample, with minimal contamination, through the use of concentrated solar radiation. This experimental device will allow for the evaluation of PCM technological requirements and is intended to aid in determining the technical challenges involved.

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A. Materials Considerations and Crucible Design

Elemental boron is highly reactive in both solid and liquid forms as temperatures approach the melting point[32] (approx. 2570 K for amorphous boron[33]). As a result, physically containing boron with minimal contamination in a liquid state is problematic due to its high reactivity with the limited number of materials capable of withstanding the necessary experimental temperatures. A literature review indicated that molten boron has been created in the presence of refractory metals, graphite, and ceramics with varying contamination levels.[17]

Refractory metals have been utilized for the construction of effusion cells to create high purity boron thin films via vacuum vapor deposition.[34-39] In these studies, however, contamination is measured in the thin films produced and not within the bulk boron source. Further, these tests do not specify if the contaminating compounds formed at high temperature might produce a protective layer that prevents further reaction (as in the case of aluminum oxide on aluminum) or whether additional reactions and further material degradation might occur in subsequent tests (as with rust on iron). Based on inferences from the existing data, a separate experimental effort is necessary to determine the stability of refractory metals in contact with molten boron. Even if not used as a crucible material, the properties of refractory metals make them favorable in other parts of the experimental system and applicability to a future design may be determined after further contamination studies.

In contrast to the available data on refractory metals, work by Stout, et al., has evaluated the use of pure graphite as a crucible material with molten boron.[40] This testing yielded heavy boron carbide contamination of the bulk sample, indicating that solid boron carbide did not remain at the boron-graphite interface, but rather moved through the molten boron mass. It is important to note that this contamination process began only once the boron had melted, providing a further indication of the increased reactivity of boron after the transition to the liquid state.

Due to possible contamination issues with graphite and the refractory metals, ceramics, particularly boron nitride (BN), are the predominant crucible material for containing molten boron. Multiple studies cite negligible contamination of a boron sample melted in contact with BN,[40-43] which is attributable to BN's low reactivity at high temperatures and a resistance to attack in a boron-rich environment. However, additional experimental considerations must be made in the use of BN due to its strong tendency to disassociate into liquid boron and nitrogen gas at temperatures above 2300 K.[44] This disassociation can be prevented by maintaining a system pressure above the equilibrium pressure of disassociated nitrogen, and it is estimated that this pressure will be between 0.1 and 10 torr (13-1300 Pa).[45,46] Previous experimental efforts have maintained a suitable system pressure by operating in inert gas environments, or in the case of Stout et al., by sealing the boron nitride in a graphite vessel and allowing disassociated nitrogen to pressurize the container and prevent further decomposition.[40] The experimental system in development for this work relies on a nitrogen feed supplying an operating pressure of approximately 50 torr; let it be noted, however, that experimental temperatures have yet to reach the region of significant disassociation concern.

HBC grade hot-pressed boron nitride crucibles have been selected to hold the boron in the experimental system described here. HBC grade BN, in particular, was chosen due to the lack of boron oxide binders within the ceramic, which would otherwise require a high temperature bake-out procedure prior to boron contact. The crucible, shown in Figure 4, was designed to be a 0.6 x 0.6 x 0.425 inch (15.2x15.2x10.8 mm) block and contain 2 grams of powdered boron within a 0.5 inch (12.7 mm) diameter, 0.36 inch (9.1 mm) deep cylindrical cavity. The cavity design utilizes boron's relatively high absorptivity as both a solid and liquid to capture incoming radiation, and the sharp exterior corners of the crucible allow for minimal surface contact when installed in the experimental system. The thermal

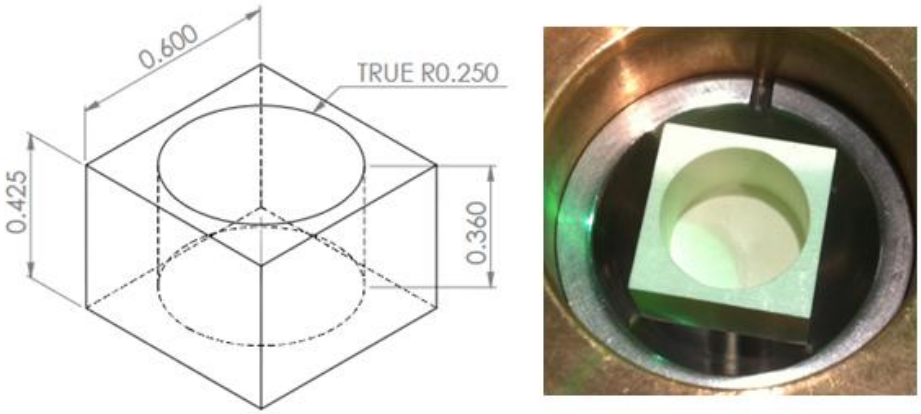

Figure 4. Schematic of the BN crucible design along with a photograph of the crucible resting in the experimental radiation shield with the top section removed.

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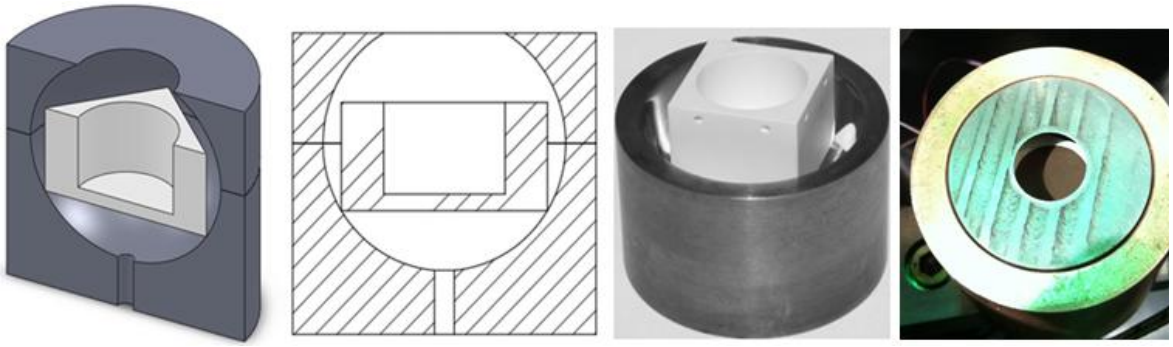

Figure 5. Model views and photographs of the BN crucible and molybdenum radiation shield. From left to right: 1) Cross section model view of shield with crucible, 2) Drawing view showing an overall high view factor from the crucible to the shield surface, 3) Photograph of the bottom section of radiation shield with crucible inset, 4) Top-down photograph of the assembled radiation shield with a boron filled crucible visible through the top opening.

conductivity of BN is higher than that of most ceramics (25 W/mK), but is still low enough to allow relatively large thermal gradients during the heating process, as was observed during initial experimental testing. As the design of the crucible is refined, it is suggested that the system, including BN components, be optimized for improved heat transfer throughout the boron PCM sample.

B. Radiation Shield and Support Structure

At the melting point of amorphous elemental boron (2570K), an unshielded crucible would have grey body radiation losses in excess of 2300 W, necessitating the development of a radiation shield to reduce experimental power requirements. A solid molybdenum, 1 inch (25.4 mm) diameter, mirror-polished, spherical radiation cavity has been designed and constructed as the primary shielding mechanism to reflect and re-radiate energy back to the crucible surface. Analysis of the current system indicates an estimated reduction in radiation losses of greater than 70%, and a required maximum input power of approximately 800 Watts on the boron surface. Note that all assumptions made in these calculations were intended to overestimate the required power, and that peak power requirements are expected to occur just before the transition to liquid boron, as there is a 30% drop in the emissivity of boron when the surface becomes liquid.[47] Therefore, the 800 Watt value has been used to size the associated solar concentration system with some confidence.

As shown in Figure 5, the BN crucible rests within the mirrored cavity and maintains minimal contact with the molybdenum surface to limit conduction losses. The molybdenum shield is split in two halves to facilitate loading of the crucible; a 0.5 inch (12.7 mm) diameter hole in the top of the system provides the input for concentrated solar

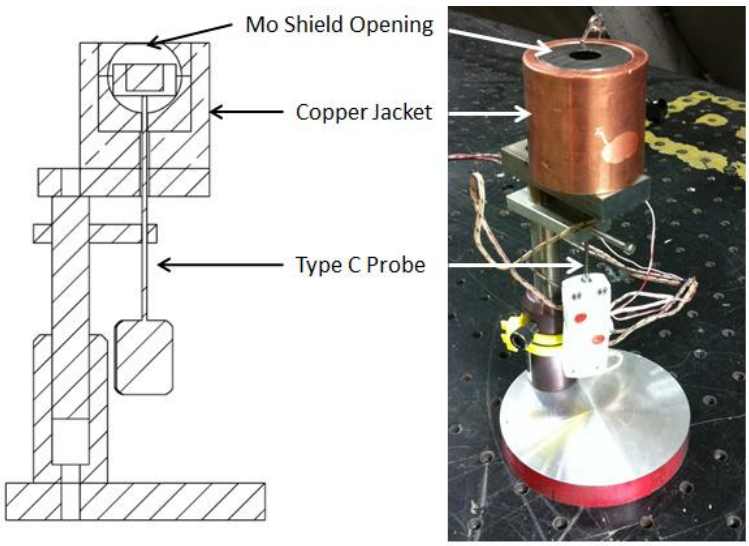

Figure 6. Copper jacket and support structure.

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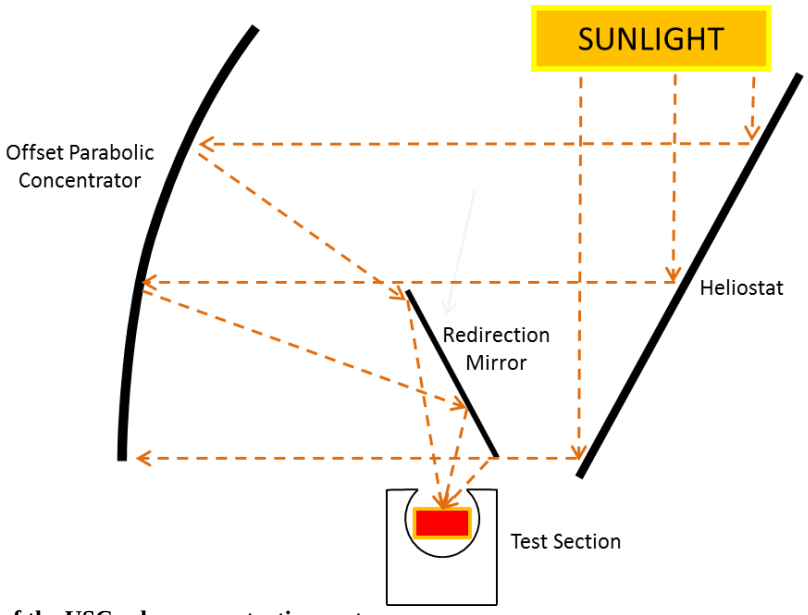

Figure 7. Schematic of the USC solar concentration system.

light, and a port is machined in the bottom of the shield to allow direct Type C thermocouple measurements of the bottom of the crucible.

In the first design iteration, the molybdenum shield is supported in a cup machined from copper; however, this will be replaced as experimental temperatures increase and further insulation of the system is required. The temperature of the shield should be kept as close as possible to that of the crucible to reach maximum radiation return to the system. The current copper support, as shown in Figure 6, actually serves to increase heat loss from the system due to its high thermal conductivity and larger exterior surface area. The next improvement to this design will be to utilize a cast zirconia oxide ceramic support cup to better insulate the system, assuming that the exterior surface of the molybdenum shield remains below the ZnO_2 breakdown temperature.

C. Solar Concentrating System Design and Construction

Utilization of concentrated solar radiation as the experimental heat source ensures direct correlation of data and techniques with future solar thermal applications. Based on the power requirements estimated above, a three-stage

Figure 8. USC heliostat and partially mirrorized 1.8 m offset parabolic concentrator.

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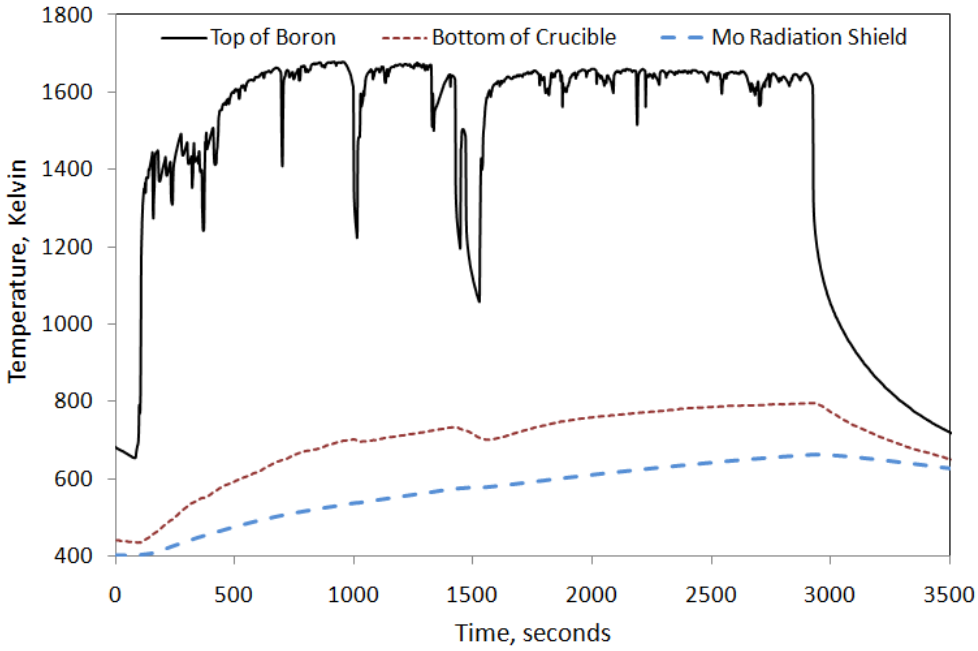

Figure 9. Sample data trace taken utilizing a thin wire thermocouple probe to measure the temperature of the top surface of the boron during on-sun testing. The fluctuations in the upper surface are the result of variations in the system optical alignment accuracy. The large dip at approximately 1500 seconds is the result of cutting radiation input to visually inspect the system.

concentration system has been designed[17] and is illustrated in Figure 7. The system is comprised of a heliostat, an offset parabolic concentrator, and a redirection mirror to direct the concentrated radiation into the vacuum chamber and test section. The base of the heliostat is a refurbished unit from previous solar thermal work conducted at the Air Force Research Laboratory (AFRL), and has been fitted with a new 8-foot by 8-foot (2.4 x 2.4 meter) mirror, as shown in Figure 8. Solar tracking is performed using a LabVIEW-controlled system and custom-written solar tracking code which provides a positional accuracy of 0.3º, which translates to 0.125 inches (3.2 mm) at the focal point The off-set parabolic concentration dish is being derived from a Prodelin series 1194 fiberglass Ku-band reflector, also shown in Figure 8, via the Spectra Chrome process. Placement of the facility within the urban USC campus allows for approximately 4 hours of full illumination per day.

The collection and concentration system is designed to provide a power of 1000 W at the focal point with a total heliostat-to-boron-surface transfer efficiency of 56%. This power level should be sufficient to melt a boron sample within the first iteration of the crucible housing described above, and will certainly continue to provide adequate radiative flux for future refined systems. As shielding and insulation methods improve, the total required power for the system is expected to drop, and evaluation of larger and more complex systems will be possible.

D. Initial Data and Thermal Concerns

To date, the USC system has operated at 10% system power, as measured via radiant flux measurements at the focal point, using a smaller, partially masked concentrator. Running the system at reduced power levels allows simpler evaluation of temperature measurements, heliostat controls, and general experimental operations. At this low power level, empty BN crucibles crucibles have been heated to temperatures over 900 K. Further, the system has been tested utilizing sub-micron amorphous boron powder (over 99% pure) that has been packed into the BN crucibles to create a smooth top surface for absorbing radiation. Packing of the boron particles further serves to reduce the quantity of trapped gases within the powder. During initial tests in which the boron powder remained relatively loose, expanding gases within the powder caused up to one third of the boron mass to be ejected from the crucible during heating. When testing a crucible containing packed boron powder, data taken from the bottom of the crucible via a Type C thermocouple probe showed temperatures roughly 100 K below those seen in empty crucible testing. However, optical inspection comparing the brightness of the upper exposed BN surfaces on boron loaded crucibles to those seen during empty crucible testing indicated higher temperatures being achieved at the top of the crucible surface.

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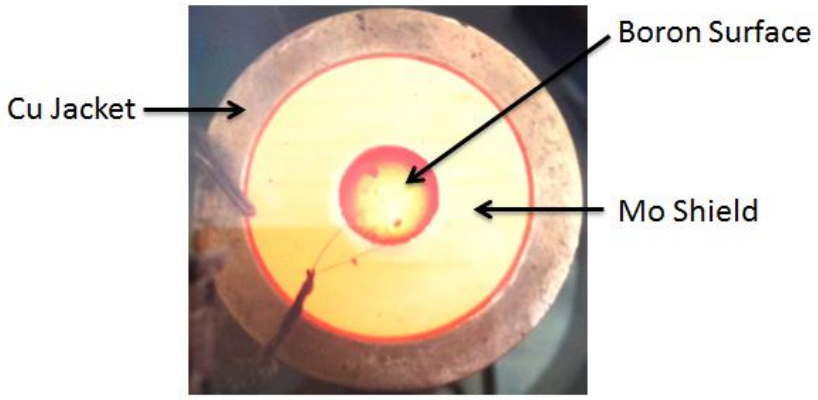

Figure 10. Top-down photograph of the experimental test section immediately after halting the solar radiation input. The center area is the boron surface and shows relatively steep thermal gradients in the radial direction. The dark spots in the center of the image are larger masses of boron disturbed during installation of the embedded thermocouple.

To determine the temperature gradient across the crucible, a bare thin-wire type C thermocouple was buried in the boron sample and the first contact junction between the positive and negative thermocouple leads was positioned at the upper boron surface. Data taken using this method, illustrated in Figure 9, indicates a maximum upper surface temperature in excess of 1650 K, with a temperature difference of almost 900 K across the boron-crucible system. There also appears to be large thermal gradients in the top boron surface itself and thermocouple measurements indicate a high sensitivity of this temperature to differences in system optical alignment. Figure 10 illustrates the large radial thermal gradient across the upper surface; this was not observed in empty crucible testing and the assumed temperature profile coincides with the relative intensity of the incoming solar radiation.

All boron testing has resulted in a discoloration of the boron surface, shown in Figure 11, that matches the thermal profile apparent in Figure 10, with the (cooled) boron powder transitioning from a grey-black surface at the hottest point to the original brown color at the crucible edges. It is believed that this discoloration process is temperature dependant and is not occurring due to reactions with gaseous species in the chamber. Tests are operated at pressures of approximately $8x10^{-6}$ torr and the boron sample is allowed to outgas for multiple hours before testing. In additional tests, a BN cap was used to cover the boron surface and directly absorb the incoming solar radiation; this eliminated the discoloration phenomena as the BN surface likely shielded the boron sample from reaching the highest temperatures.

The temperatures reached at the (uncovered) upper boron surface are sufficient to cause a recrystallization of the boron and the boron discoloration is possibly explained by a transition in the hottest regions from amorphous to β-rhombohedral form.[48,49] This discoloration process also reveals the shape of thermal gradients within the boron sample. As shown in Figure 11, removing layers of boron from the top of the heated sample reveals a discoloration area of decreasing radius, indicating a low thermal conductivity within the packed powder. The effective thermal conductivity of the packed boron sample is on the order of 10 W/mK and is considerably lower than that of the surrounding BN container.[50] This leads to the large overall thermal gradients in the crucible system that were measured by direct thermocouple readings.

Once full power testing of the system begins, it is expected that the thermal gradients present in the crucible will lessen as the effects of the radiation shield should increase with temperature and return more heat to the lower

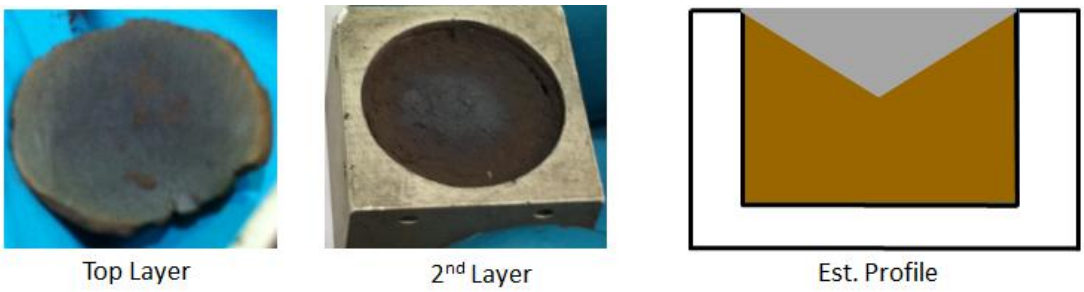

Figure 11. Discoloration pattern in the boron sample indicative of large thermal gradients.

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portions of the crucible. The initial results, however, indicate that the relatively low thermal conductivities will likely result in temperatures at the upper surface of the boron sample that far exceed the design temperature of 2570 K. A more effective crucible design will need to incorporate a means of conducting incoming radiation efficiently through the entire boron PCM mass to reduce localized thermal loads and bring the entire crucible toward an isothermal state.

V. Conclusion

Research indicates that bimodal solar thermophotovoltaic systems utilizing boron for thermal energy storage would yield significant advancements for solar thermal power and propulsion systems applicable to microsatellites. Evaluations of the required components and materials indicated that the basic components required to construct and test a molten boron thermal energy storage system currently exist, but a significant effort will be required to demonstrate such a system, with a particular emphasis on identifying materials with high temperature handling capabilities and long-term compatibility. Assuming these designs can be completed and implemented in the relatively far-term, a boron-based system could provide a low mass, high-efficiency energy storage and propulsion system, enabling very high capability microsatellites in low Earth orbit. An experimental effort is underway at the University of Southern California to evaluate the potential of molten boron phase change energy storage systems, including necessary solar concentration systems, along with equipment and materials required to contain and insulate high temperature molten boron. Initial results indicate that while significant thermal insulation and conduction concerns remain, melting boron with concentrated solar light is within probable experimental capabilities.

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